GIANT AND 'DOUBLE-DOUBLE' RADIO GALAXIES: IMPLICATIONS FOR THE EVOLUTION OF POWERFUL RADIO SOURCES AND THE IGM

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Giant radio sources form the linear size extreme of the extra-galactic radio source population. Using the WENSS survey, we have selected a complete sample of these sources. We have investigated the properties of their radio structures. We find, among other things, that these sources are old (50-100 Myr) and have higher advance velocities than smaller sources of similar radio power. We find pressure gradients in their radio lobes, suggesting that the lobes are still overpressured with respect to the environment. Further, we find no evidence for a cosmological evolution of the radio lobe pressures with increasing redshift, at least up to $z \sim 0.4$, other than that caused by selection effects. We argue that a much fainter sample of giant sources than currently available is needed to constrain the pressure in their environments, the IGM, and that SKA can play an important role in studying such sources. Another extremely important discovery is that of a population of radio sources with a so-called 'double-double' structure, i.e. that of a small two-sided radio source embedded inside a much larger two-sided structure. We argue that these sources result from an interrupted central jet-forming activity. As such, they are the most convincing examples of radio sources with a history of interrupted activity, yet. Since the inner lobes advance within the outer lobes, high resolution low frequency (~ 200 MHz) polarization studies may reveal the constituents of radio lobes and cocoons. We thus argue for a SKA design that can provide low-frequency images at arcsec resolution, but which is also sensitive to structures as large as a few tens of arcminute on the sky.

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1 Giant Radio Galaxies

The central activity in radio loud Active Galactic Nuclei (AGN) produces relativistic outflows of matter, the so-called 'jets', for a prolonged period of time, possibly up to a few 10^8 yr. These jets, when powerful enough, inflate a cocoon (e.g. [1], [2]) which expands first in the Interstellar Medium (ISM) and later in the Intergalactic Medium (IGM). Within this cocoon, which exists of accelerated jet material, synchrotron radio emission is produced. The evolution of the cocoon can therefore be traced by observations of the radio lobes.

Giant radio galaxies (GRGs) are radio sources whose lobes span a (projected) distance of above 1 Mpc[b]. Since radio sources grow in size as they get older (e.g. [1], [3]), GRGs must represent a late phase in the evolution of radio sources.

Probably not all sources will live long enough, or grow rapidly enough, to reach the size of the Giant radio sources. What fraction of sources do and under what circumstances is still unclear. According to radio source evolution models, GRGs must be extremely old (i.e. typically above 10^8 yr) and/or located in very underdense environments, as compared to smaller radio sources (e.g. [4]). The age of a radio source can be estimated by sensitive multi-frequency radio observations of the radio lobes (e.g. [5]). The first systematically obtained results of a small sample of GRGs show that the spectral ages so found are indeed comparable to those expected from source evolution models [6]. However, such studies have always been severely hampered by the fact that large uniformly selected samples of GRGs do not exist.

Since GRGs have sizes which are considerably larger than galactic or even cluster halo cores, their radio lobes interact with the intergalactic medium (IGM). Therefore, by studying the properties of the radio lobes we can constrain the properties of the IGM. For instance, in an adiabatically expanding Universe filled with a hot, diffuse and uniform IGM, the IGM pressure, p_{igm}, should increase as a function of redshift, z, as $p_{igm} \propto (1+z)^5$ (e.g. [7]). Using a small sample of GRGs, Subrahmanyan & Saripalli [7] limit the local value of the IGM pressure, $p_{igm,0}$, to $p_{igm,0} \lesssim 2 \times 10^{-14}$ dyn cm^{-2}. Cotter [8] performs a similar analysis with a larger sample of sources which also extends to higher redshifts (up to $z \sim 1$), and he confirms that the observed evolution in radio lobe pressures does not contradict a $(1+z)^5$ relation. However, these results might be biased since it is likely that the known distant GRGs are the most powerful ones at that epoch and which thus have the highest equipartition lobe pressures.

In order to address the above issues more carefully, it is vital to use a sample of GRGs with well understood selection effects. We have compiled such a sample of GRGs from the 325-MHz Westerbork Northern Sky Survey (WENSS; e.g. [9]). From the WENSS we have selected all radio sources with a (projected) size exceeding 1 Mpc, a flux density above 1 Jy, an angular size above 5 arcminutes and a distance from the galactic plane larger than 12.5 degrees. Our sample consists of 26 sources, of which 10 are newly discovered GRGs [10].

We have used the WENSS radio maps, in combination with maps from the 1.4-GHz NRAO VLA Sky Survey (NVSS, [12]) and our 10.5-GHz Effelsberg observations to study the properties of the radio lobes of the 22 FRII-type [13] sources in our sample. Since GRGs are large sources on the sky, it is already possible to achieve this with the modest angular resolution of these datasets (i.e. ~ 1 arcmin). In cases where we could determine the spectral age from a steepening of the lobe spectrum away from the hotspot, we find ages which are in the range of 50 – 100 Myr, which agrees with earlier results on GRG spectral ages (e.g. [6]). We also find that the GRGs tend to have higher lobe advance velocities than smaller sources of similar observed radio power [10].

2 Radio lobe pressure evolution

Estimates of the internal pressures of radio lobes are directly obtained from estimates of the equipartition energy densities, u_{eq}, since in a relativistic plasma the pressure is given by $p = \frac{1}{3}u$, where u is the energy density. The equipartition energy density u_{eq} can be obtained from radio observations (e.g. [11]).

[b]We use $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout this contribution.

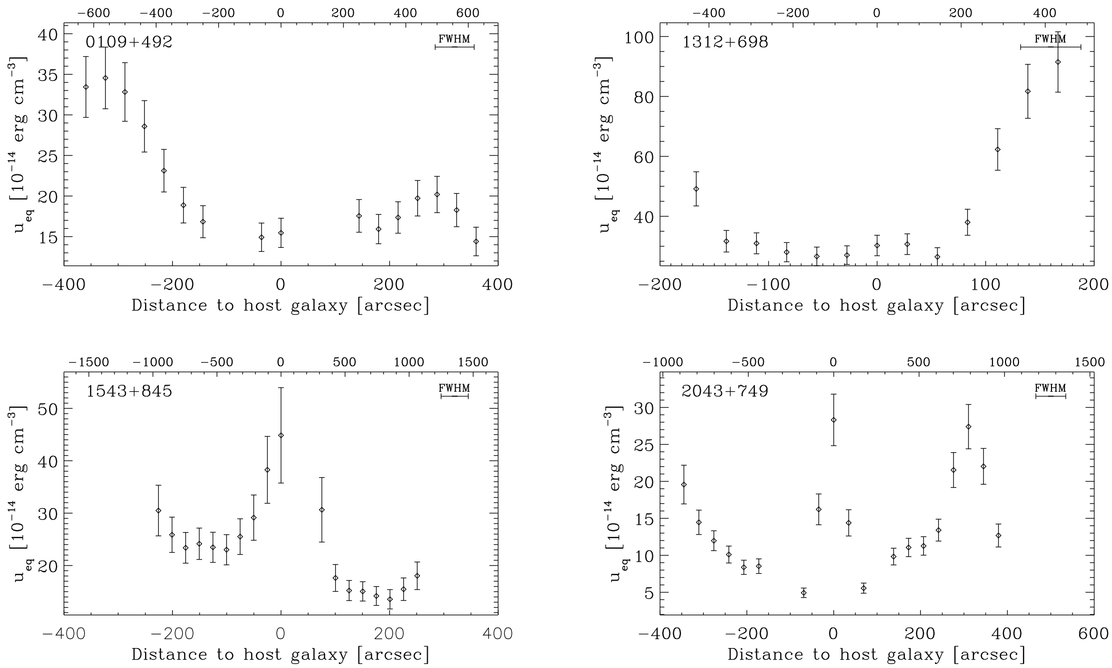

Figure 1: Energy density profiles along the radio axes of the GRGs B 0109+492 (upper left), B 1312+698 (upper right), B 1543+845 (lower left) and B 2043+749 (lower right). Numbers along the top denote the distance from the core in kpc. Note the increase of the energy density (or, equivalently, pressure) towards the outer edges of the sources. Also note the increase towards the center in B 1543+845 and B 2043+749; the latter has a strong radio core causing this effect, but the former has not.

If a radio source is well resolved (i.e. larger than 8 arcminute), we have divided the radio lobe into several regions and estimated the energy density in each of these. We have made measured the radio lobe pressure along the radio axes of the FRII-type sources. In Fig. 1 we have plotted four examples of energy density (i.e. pressure) profiles of GRGs. All sources presented here show a decrease in energy density when going back from the hotspots (situated at the outer edges) to the radio cores in the center. In some cases, the energy density rises again in the vicinity of the center. This can be either due to the presence of a strong radio core and/or jet, or to a real increase in the lobe pressure as a result of a higher pressure in the environment caused by the presence of, e.g., a gaseous galactic halo. The decrease in energy density as a function of hotspot distance indicates the presence of a pressure gradient in the lobes. This suggests that the radio lobes are still overpressured with respect to the ambient medium, the IGM.

We have also calculated the intensity weighted average lobe energy density for each source in our sample. Fig. 2 shows these values plotted against the redshifts of the sources. We have made a separation between sources which are smaller and larger than 2 Mpc (closed and open symbols, respectively). There are two things to note in this plot. First, the larger sources tend to have the lowest average lobe pressures. This is a confirmation of the trend already noted by Cotter [8] for sources smaller and larger than 1 Mpc. Second, although the redshift range of our sources is limited ($z \lesssim 0.4$), there appears to be a correlation between energy density and redshift. This agrees with the results from Saripalli & Subrahmanyan [7] and Cotter [8] and does not contradict a $(1+z)^5$ increase of the IGM pressure, provided that the current day value is $\lesssim 10^{-14}$ dyn cm^{-2} (indicated by the dotted line in Fig. 2).

We note, however, that the observed increase in lobe energy density with increasing redshift in Fig. 2 also exactly matches the expected behaviour for a source of fixed dimensions and flux density. This is shown by the dashed line in Fig. 2, which indicates the expected equipartition energy density in the lobes of a source with a size equal to the median size of the GRG sample and a flux density equal to the median flux density of the sample. The slope of this line matches the observed redshift relation of the

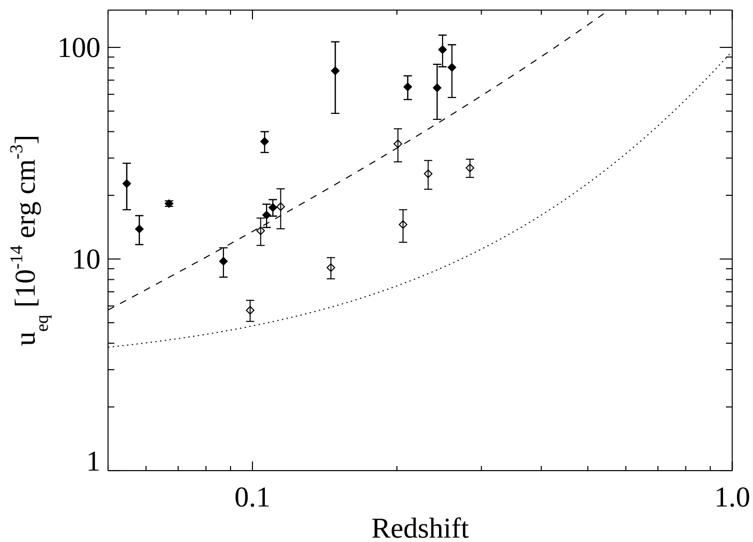

Figure 2: A plot of the intensity weighted average equipartition energy density in the radio lobes of the FRII-type GRGs in our sample against redshift. Filled symbols denote sources with a linear size between 1 and 2 Mpc, open symbols are sources above 2 Mpc. The dashed line indicates the expected energy density of a source with a flux density, volume and spectral index as given by the median values of these properties in our sample, and thus gives the relation which is expected on basis of our selection criteria. The dotted line indicates the lower limit if the pressure in the lobes is dominated by relativistic particles, the lobes are in pressure equilibrium with the IGM and the pressure of the IGM follows the relation $p_{igm} = 1.0 \times 10^{-14} \cdot (1+z)^5$ dyn cm^{-2}.

energy density in our sources. Therefore, the observed redshift relation is more likely due to the use of a flux density and source volume limited sample, than to any cosmological effect. The same relation must apply to the sources of Cotter [8], since his sample of high redshift GRGs also form a flux density limited sample (flux density between 0.4 and 1.0 Jy at 151 MHz) of sources larger than ~ 1 Mpc. We conclude that there is therefore no evidence for a strong increase in the IGM pressure with increasing redshift, although we cannot reject it either.

To investigate whether the IGM pressure truly evolves as strongly as $(1+z)^5$, it would be necessary to find Mpc-sized radio sources at high redshifts. From Fig. 2 it can be deduced that the existence of a population of sources with lobe energy densities of $\lesssim 3 \times 10^{-14}$ erg cm^{-3} at redshifts of at least 0.6 would be difficult to reconcile with a strong pressure evolution, unless the current day IGM pressure is much lower than 10^{-14} dyn cm^{-2}. Such sources are expected to have flux densities of $\lesssim 200$ mJy at 325 MHz (assuming a size of 1.5 Mpc, a spectral index of -0.8 and a aspect ratio of 3), and are thus detectable by WENSS. Indeed, we have started to compile a sample of such sources. Detailed observations of their radio structures at low frequencies (i.e. ~ 100 MHz) will be necessary to correctly estimate the lobe energy densities.

3 'Double-double' radio galaxies

One of the outstanding issues concerning extra galactic radio sources and other Active Galactic Nuclei (AGN) is the total duration of their active phase. For radio sources, this physical age of the nuclear activity is not to be confused with the radiative loss age determined from radio spectral ageing arguments; many extra galactic radio sources probably have a physical age well surpassing their radiative loss age (e.g. [14], [15], but also see [16]). The length of the active phase is intimately related to the possible existence of duty cycles of nuclear activity. In case nuclear activity is not continuous,

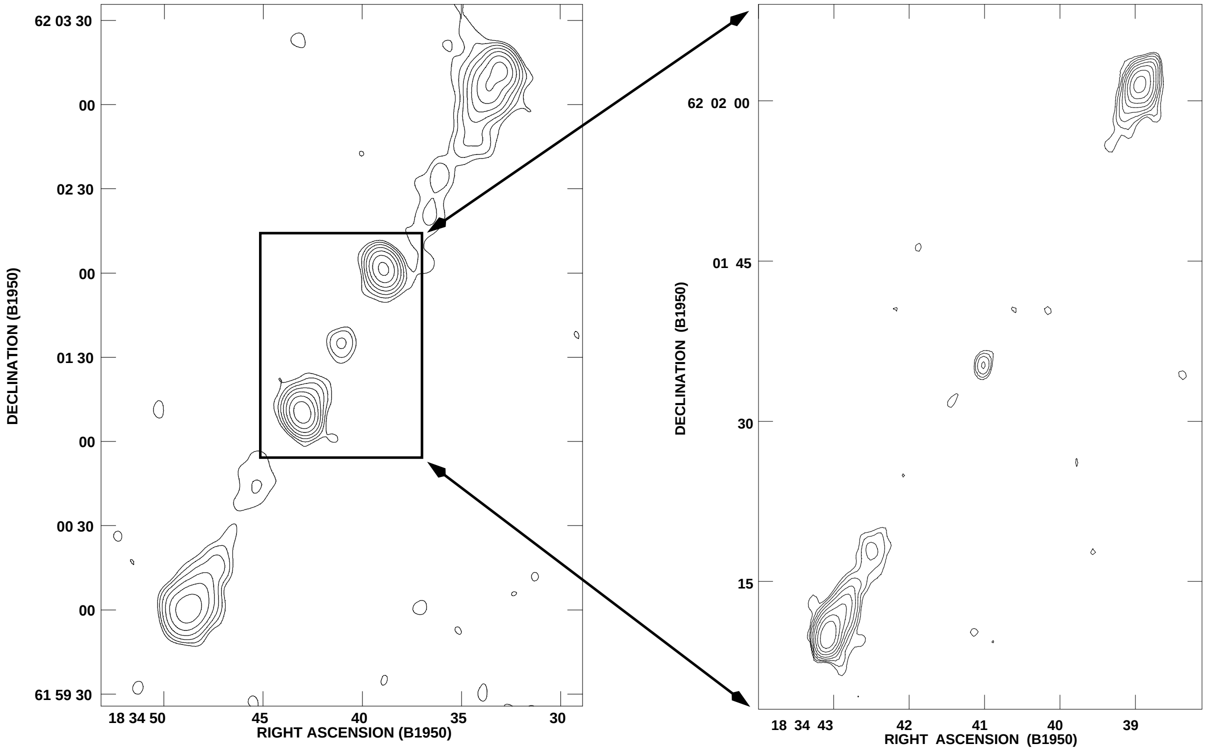

Figure 3: A radio contour plots of the DDRG B 1834+620. On the left we present a map from 8.4-GHz VLA observations (8 arcsec resolution), which clearly shows the outer lobe structures. The map on the left shows the inner structure at a higher resolution of ~ 1 arcsec and at a frequency of 1.4 GHz. Clearly, the morphology of the inner structure is that of an FRII-type radio source. The overall size of the outer structure is 1660 kpc, that of the inner structure 420 kpc. The redshift of this source is 0.519 . Contours are drawn at intervals of a factor 2 starting at 0.22 mJy beam^{-1} (8.4 GHz) and 0.17 mJy beam^{-1} (1.4 GHz). Dashed contours denote negative levels.

how often do interruptions occur and how long do they last?

Such duty cycles can only be recognized if there is some mechanism to preserve the information of past nuclear activity for a long enough time to be recognized when a new cycle starts up. In extended radio sources, such a mechanism is potentially provided for by the radio lobes, since they remain detectable for a long time after their energy supply has ceased (possibly up to a few 10^7 yr; e.g. [17]). If a new phase of activity should start before the 'old' radio lobes have faded, and if this activity manifests itself by the production of jets, we can in principle recognize this by the observation of a new, young radio source embedded in an old, relic structure. One well-known candidate for such a 'restarted' radio source is the radio galaxy 3C 219 ([18], [19], [20]). In this source, radio jets have been observed which abruptly become undetectable at some point between the core and the leading edge of the outer radio lobes. However, sources such as this are extremely rare and difficult to recognize.

During our search for GRGs in the WENSS survey, we have found several sources which are excellent candidates for restarted radio sources. Radio contour plots of two of these, B 1834+620 and B 1450+333, are shown in Figs. 3 and 4, respectively. Both cases are clearly different from 'standard' FRII-type radio galaxies. Since they consist of an inner double-lobed radio structure as well as a larger outer double-lobed structure, we have called these sources 'double-double' radio galaxies (DDRGs; [10], [21], [22]).

In Schoenmakers et al. ([10], [21], [22]) we present a small sample of seven of these peculiar sources. Among the general properties are that in all cases the inner structures are less luminous than the outer

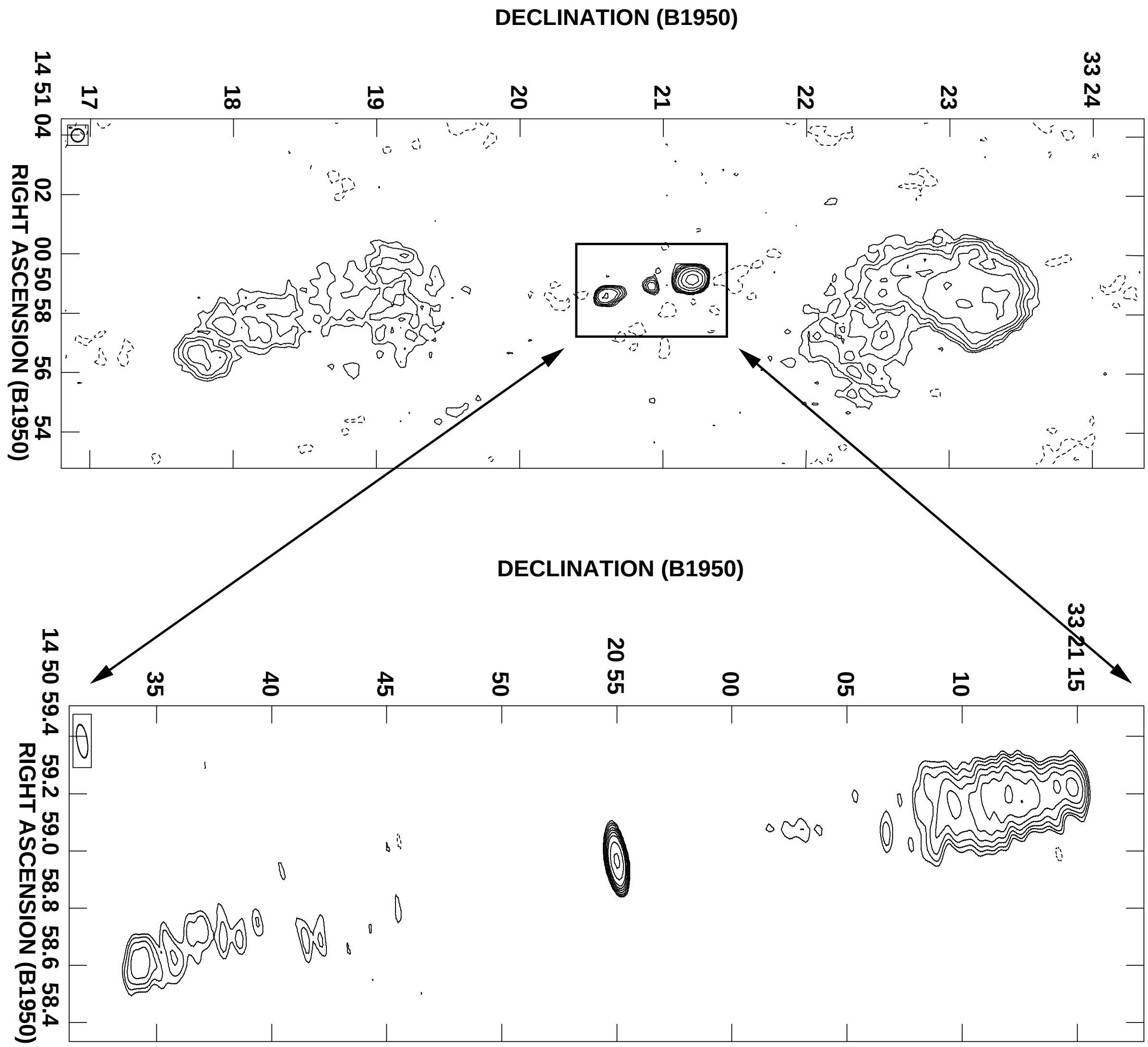

Figure 4: A radio contour plots of the DDRG B 1450+333. At the top we present a map from the 1.4-GHz VLA FIRST survey [24], at the bottom we shows the inner structure at a higher resolution and at 4.9 GHz. Clearly, the morphology of the inner structure is that of a FRII-type radio source. The overall size of the outer structure is 1680 kpc, that of the inner structure 180 kpc. The redshift of this source is 0.249 . Contours are drawn at intervals of a factor $\sqrt{2}$ starting at 0.45 mJy beam^{-1} (1.4 GHz) and 0.12 mJy beam^{-1} (4.9 GHz). Dashed contours denote negative levels.

structures, and that the difference in radio power between the inner and outer structures appears to decrease with increasing size of the inner structure. Further, almost all sources in our small sample have large linear sizes, above 700 kpc and ranging up to 3 Mpc.

The observed two-sidedness and symmetry in the morphology of the inner structures strongly suggests a central cause for this phenomenon, and we believe that an interruption of the central jet-forming activity is the most likely one. For the source B 1834+620 (Fig. 3) we are able to constrain the time-scale of the interruption to $\lesssim 6$ Myr ([22], [23]). What actually causes the AGN to interrupt the radio activity is unclear. Possible options are a large inflow of gas into the central region of the galaxy (e.g. by an infalling large molecular cloud), causing an instability in the accretion flow onto the central massive black hole.

One of the most fascinating aspects of these sources is the actual existence of the inner radio lobe structure. Numerical simulations of restarting systems (e.g. [19]) and physical considerations on the

properties of cocoons produced by jets agree in that the density inside cocoons are not high enough to allow the formation of strong shocks, related to the formation of hotspots and radio lobes. The fact that we nevertheless observe these must indicate that the density inside the cocoons is much higher than predicted by these models. Kaiser et al. ([25]; also see [10]) present a model in which the density inside the cocoon is actually increased as the result of the entrainment and subsequent shredding of warm clouds in the IGM by the expanding cocoon. They show that after a long enough time (i.e. a few 10^7 yr) the density inside the cocoon may have increased sufficiently to allow a new system of lobes and hotspots to be formed after an interruption of the jet flow. The long time scale can explain the large size of the DDRGs. The low densities inside the cocoon as compared to the ambient medium can explain the low radio power and the high advance velocities of the inner structures (estimated to be $0.2c$ – $0.3c$ ([10], [22], [23]).

We therefore argue that the DDRGs show a distinct phase in the evolution of radio sources. Among the questions that remain are the following: How many radio sources actually go through such a phase? What is the cause of the interruption? To answer these questions much more detailed studies of these fascinating sources are required. To investigate the rate of occurrence, it might be interesting to search for old relic structures around known radio sources. Such an undertaking must be performed at low frequency, with high sensitivity and dynamic range. With the proposed sensitivity of SKA, this should be a feasible project. The cause of the interruption can perhaps be investigated by detailed optical and kinematical studies. However, the chance of finding anything may actually be small if the cause is only due to small-scale events such as an infalling cloud.

4 The importance of SKA

The next important step in GRG research will be the compilation of a large sample of higher redshift GRGs. This is interesting in many respects: First of all, such a sample will provide us with important constraints on the cosmological changes in radio source evolution. Since this is closely related to the evolution of the environments of radio sources on scales up to a few Mpc, this can teach us more about the coupling between the evolution of galaxies in clusters and the intra-cluster gas. Second, sensitive high resolution observations are needed to investigate the radio lobe properties of high redshift GRGs in some detail. This is vital to obtain information on the spectral ages of GRGs, and the ageing processes themselves. Since the energy density of the microwave background increases as $(1+z)^4$, the effect of Inverse Compton scattering on the ageing of the particles in the radio lobes becomes increasingly more important toward higher redshift. This will make the radio spectra of the bridges in the lobes steepen considerably, allowing only sensitive low frequency observations to detect these faint regions. Detailed studies of the rotation measures towards the radio lobes can show us density structures in the ambient medium of the lobes at distances of a Mpc from the host galaxy. Also, if part of the Faraday rotation were to occur within the radio lobes, such a study may yield unique information on the internal properties of the radio lobes, such as the thermal particle density and the magnetic field strengths.

In case of the DDRGs similar studies can reveal the properties of the medium around the inner lobe structures, and can thus play an important role in testing the model proposed by Kaiser et al. [25] for the formation of these structures. Another important topic is how common the DDRG phenomenon is, a question which is closely related to that of the occurrence of duty-cycles in AGN. The DDRGs which we know now are the ones with the most prominent outer structures and as such that may only form the tip of the iceberg of radio sources with multiple periods of activity. With a sensitive low frequency telescope we can investigate the areas surrounding known radio sources for possible relic structures, indicative of an earlier phase of activity.

Therefore, the properties that will make SKA an extremely important instrument for future research of GRGs and DDRGs are a high (sub-arcsecond) angular resolution at a low frequency (100 – 1000 MHz), combined with excellent sensitivity and polarization characteristics. In order to be able to investigate such large structures as GRGs are, SKA should be capable of mapping large structures on the sky, up to a few tens of arcminute, without losing sensitivity. We therefore argue for a next generation radio telescope (i.e. SKA) which consists of a combination of a central compact array (few km diameter) and

several long baselines (preferably up to a thousand km), which should be able to observe routinely at frequencies as low as 50–100 MHz.

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